DEVELOPMENT OF THE CRITICALITY CONTROL OVERPACK PAYLOAD CONTAINER FOR TRANSPORT OF EXCESS PLUTONIUM OXIDES IN THE TRUPACT-II AND HALFPACT PACKAGINGS

Brad A. Day
Nuclear Waste Partnership LLC
4021 National Parks Highway
Carlsbad, NM 88220

ABSTRACT

A new transuranic (TRU) waste payload container has been developed for the shipment of a target waste stream consisting of approximately 9 metric tonnes of excess plutonium oxides in the TRUPACT-II and HalfPACT Type B packages. The Criticality Control Overpack (CCO) is designed to increase the authorized fissile material content of each package by a factor of 1.9 times the current limits with a 30% reduction in fabrication costs as compared to existing authorized fissile material centric payload container options. Confinement and separation of fissile material within and between individual CCOs in 14 pack and 7 pack arrays of payload containers results in a ^{239}Pu fissile gram equivalent (FGE) limit per package of 5,320 and 2,660 FGE for the TRUPACT-II and HalfPACT packages, respectively. Hypothetical Accident Condition (HAC) 30 foot drop certification testing of the CCO was performed at elevated normal conditions of transport (NCT) temperatures to demonstrate the ability of the payload container design to perform its safety-significant criticality control function. The CCO design consists of a steel 55-gallon drum overpacking an inner stainless steel Criticality Control Container (CCC) (constructed from 6” class 150 standard ASME pipe and flange components) and impact-attenuating upper and lower plywood dunnage assemblies. This paper discusses the design, development, structural certification testing, and thermal and criticality analysis of the new CCO payload container.

INTRODUCTION

The CCO consists of an approximately 24-inch diameter by 35-inch tall steel 55-gallon drum containing a CCC confinement vessel that is centrally positioned within the drum by laminated plywood dunnage. It is designed to be used for shipment of increased fissile waste contents in the TRUPACT-II and HalfPACT packages. The TRUPACT-II and HalfPACT packages, shown in Figures 1 and 2, can accommodate an assembly of fourteen (14) and seven (7) CCOs, respectively.

The CCC is constructed of 304/304L stainless steel 6-inch Class 150 standard blind and slip flanges and Schedule 40 pipe (NPS). The lid of the CCC is sealed with an aramid-inorganic/nbr standard ring gasket and retained with eight (8) 3/4-inch heavy hex head stainless steel bolts. The lid and base of the CCC are nominally 1 inch thick and the pipe shell is nominally 0.28 inches thick with an overall assembly height of approximately 29-1/2 inches. The CCO has an approximate tare weight of 230 pounds and a maximum gross weight of 350 pounds. A lifting attachment is optionally integrated into the CCC lid to facilitate handling. Partially exploded views of the CCO and CCC are provided in Figure 3 and Figure 4, respectively. Both the 55-gallon drum of the CCO and the CCC must be fitted with a filter vent.

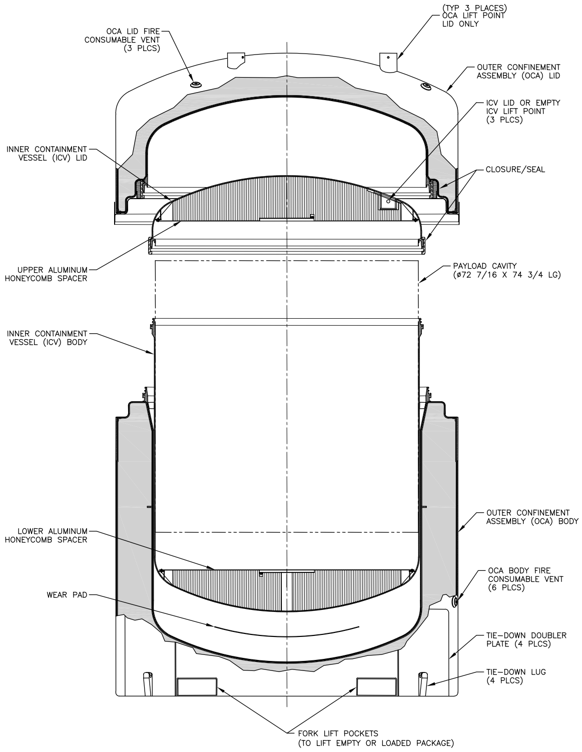

Figure 1. TRUPACT-II Packaging

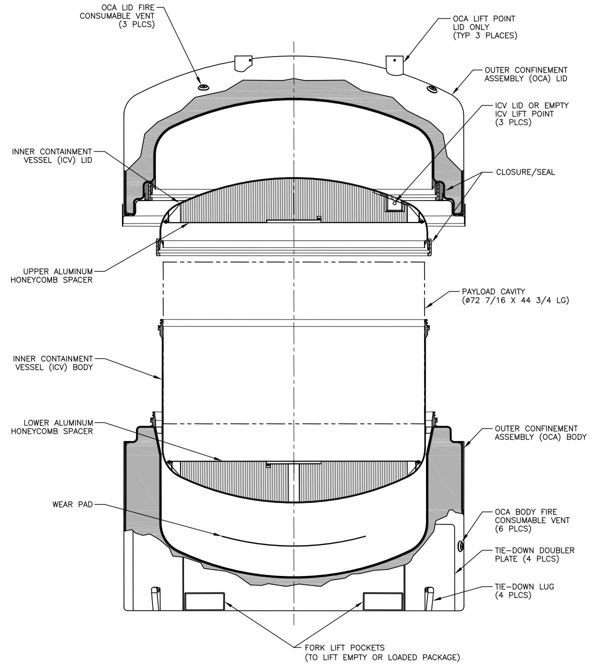

Figure 2. HalfPACT Packaging

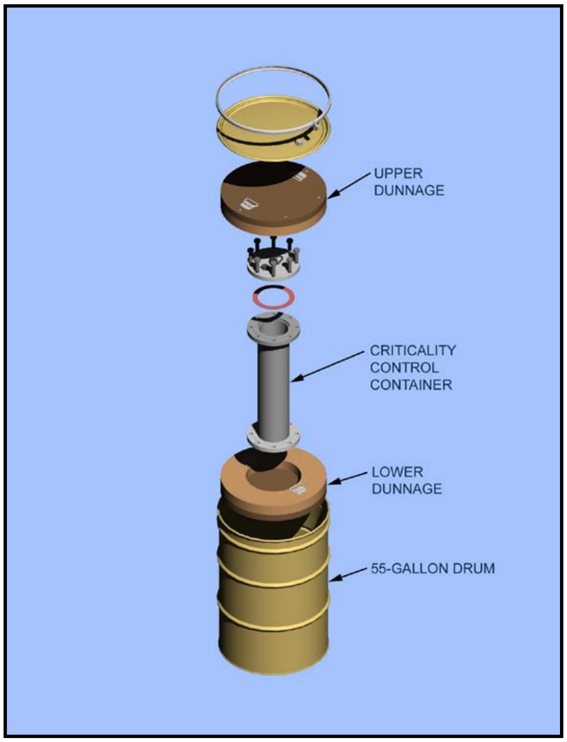

Figure 3. Criticality Control Overpack

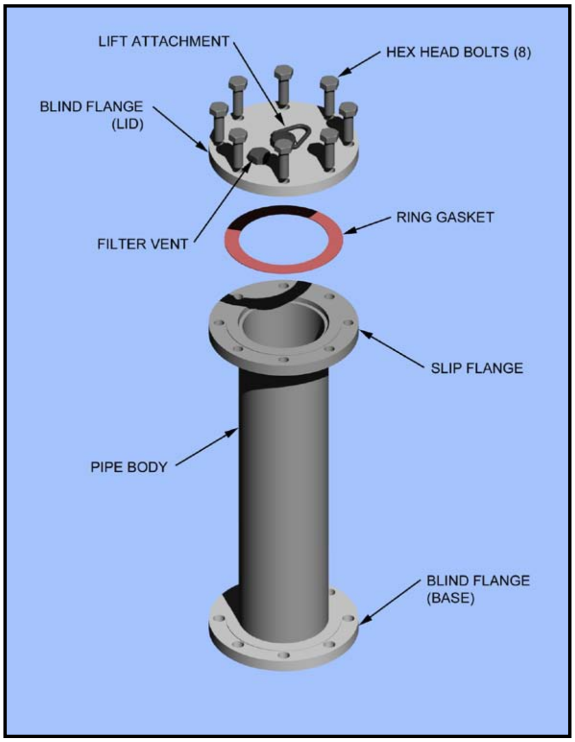

Figure 4. Criticality Control Container

STRUCTURAL EVALUATION

Hypothetical Accident Condition Free Drop Testing

To demonstrate confinement, shielding integrity, and adequate array spacing for criticality control of the CCO, a full-scale test program was conducted.[1] Two CCO test articles were assembled and attached to side and end drop test fixtures comprised of plate steel to conservatively simulate the overburden forces and boundary conditions associated with a payload assembly of CCOs within the TRUPACT-II packaging Inner Containment Vessel (ICV). The impact-attenuating characteristics of the TRUPACT-II Outer Confinement Assembly (OCA), with its energy-absorbing polyurethane foam, was conservatively neglected from consideration in the tests. Each CCO test article and associated drop test fixture was subjected to a 30-foot free drop onto a flat, essentially unyielding, horizontal surface: one horizontal side drop and one vertical top-down end drop with the CCO at elevated temperature (>200 °F) conditions.

At the conclusion of the 30-foot free drops, the CCO test articles were dimensionally inspected to determine the radial crush deformation due to the side drop and the axial crush deformation due to the end drop. The CCC test articles were also disassembled from the CCOs, misted with water, and visually examined for the presence of fluorescein dye to verify confinement integrity. To conservatively test to the maximum allowable CCO gross weight of 350 pounds, each CCO test article was directly loaded with 137 pounds of a 50/50 (by volume) mixture of lead shot and sand topped with a flour/fluorescein indicator mixture, for a total CCO test article weight of 352 pounds.

Technical Basis for Tests

To address CCO performance, it was only necessary to perform 30-foot free drop tests for the end and side orientations. Intermediate impact angles simply distribute the interaction forces at lower g-levels between the CCOs and the ICV, whereas the 0° and 90° impact orientations maximize the impact accelerations and localized bearing forces in a manner to maximize the potential for CCC confinement boundary and CCO dunnage crush damage. As such, side and end drop test orientations were bounding for the design.

Due to the maximum gross weight limit of the CCO being 350 pounds, resulting in a total payload assembly weight that is significantly lower than the 7,265-pound and 7,600-pound payload capacity authorized for the TRUPACT-II and HalfPACT packagings, respectively, the packaging response to a CCO payload was bounded by previously performed packaging certification tests. Both the side and end drops were performed on an unprotected (bare) CCO, resulting in higher deformations and acceleration loads to the CCO payload than if inside the impact-attenuating TRUPACT-II or HalfPACT packagings. Therefore, the CCO drop tests were a conservatively bounding determination of the minimum post-drop radial and axial CCO array spacing for the criticality evaluation. The CCO side and end drops were performed with the CCO test article conditioned to >200 ºF to bound the NCT elevated temperature condition. The elevated temperature maximizes the crush deformation of the plywood upper and lower dunnage assemblies, conservatively providing an upper bound on the post-drop CCO payload assembly array spacing for criticality purposes.

Side Drop

As shown in Figure 5, the CCO side drop test fixture was designed to load the CCO test article with a compressive load equal to four CCOs. The basis for the loading configuration was derived from the configuration depicted in Figure 6. The total vertical load on the bottom CCO is based on the weight of two CCOs atop the bottom CCO, plus one-half the weight from each of the four side CCOs; the other half of the weight from each of the four side CCOs is assumed to be carried by the ICV. Note that the component of horizontal compressive loading into the bottom CCO caused by the four side CCOs would tend to oppose the vertical compressive load and was, therefore, ignored to maximize overall crush and minimize radial spacing.

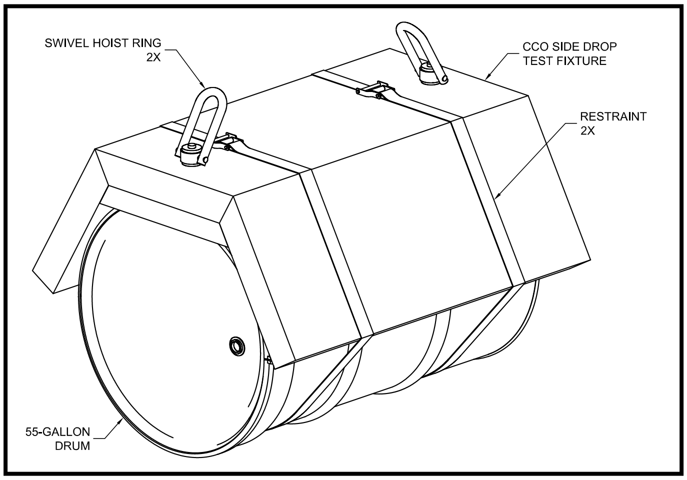

Figure 5. Side Drop Fixture

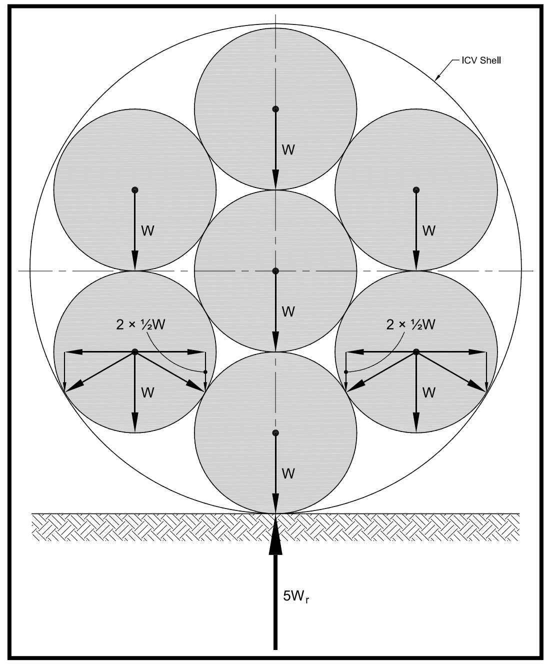

Figure 6. Side Drop FBD

The 30-foot elevated temperature side drop was performed using a CCO side drop test fixture weighing 1,452 pounds attached to the CCO side drop test article that was dropped in a horizontal orientation to radially impact directly onto the essentially unyielding drop pad surface. The test conservatively simulated the interaction between the lowest CCO and the six upper CCOs in a seven-pack array inside a TRUPACT-II or HalfPACT ICV. The test configuration neglected both the impact-attenuating characteristics of the packaging and the compliance of the upper CCOs in the array to maximize the impact accelerations on the CCC and crush deformation of the dunnage assemblies.

Post-drop inspection of the CCO indicated significant crushing of the 55-gallon drum and internal plywood dunnage assemblies that resulted in a minimum effective diameter of the CCO that measured 16¾ inches at the lid end and 15½ inches at the base end of the container (pre-drop diameter of the 55-gallon drum was ∅24 inches). The upper and lower plywood dunnage assemblies experienced a corresponding radial crush deformation, but the assemblies attenuated the impact and prevented any direct interaction between the CCC and the test fixture/test pad. The measured accelerations due to impact were recorded with filtering of the data utilizing a low-pass Butterworth 10-pole filter having a 250 Hz cut-off frequency. A minimum impact acceleration peak, on average from two sensors, of approximately 233 g's was recorded.

Disassembly of the CCO and inspection of the CCC indicated no permanent plastic deformation of any of the confinement boundary components, essentially unaltered preload of the closure bolts (maximum bolt rotation to achieve installation torque value of 3.5°), and no loss of confinement as confirmed via ultraviolet light inspection of the assembly with no presence of the fluorescein indicator on the exterior surfaces.

Figure 7 shows the CCO side drop test article and test fixture assembly prior to the drop test. Figure 8 shows the assembly during and after the side impact event. Figure 9 shows the post-test measurement of the effective diameter of the CCO and associated radial crushing of the dunnage assemblies. Figure 10 shows the CCC after the post-drop test confinement evaluation and bolt residual torque confirmation process, indicating no degradation of the confinement vessel.

Figure 7. Pre Side Drop

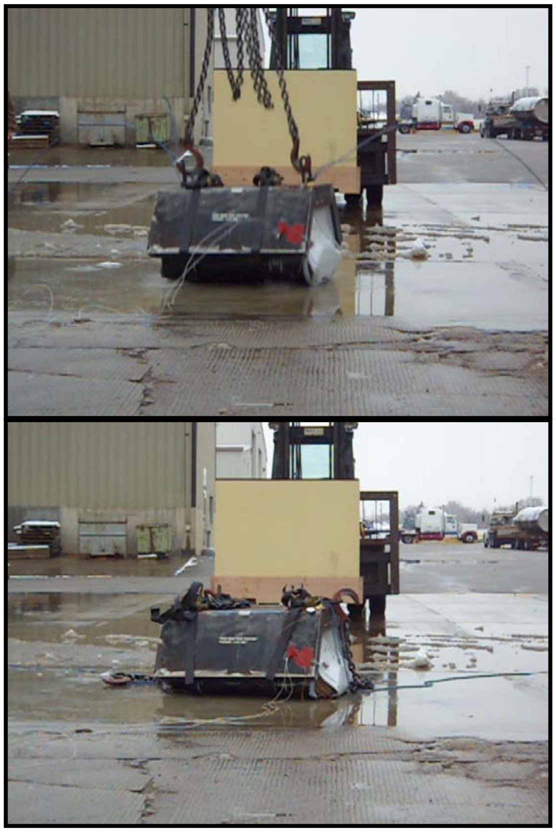

Figure 8. During and Post Side Drop

Figure 9. CCO Side Drop Inspection

Figure 10. CCC Side Drop Inspection

End Drop

As shown in Figure 11, the CCO end drop test fixture was designed to load the CCO test article with a compressive axial load equal to one CCO and to simulate the two-high drum configuration in the TRUPACT-II package that results in the maximum overall axial crush and minimum axial CCO array spacing.

The 30-foot elevated temperature end drop was performed using a CCO end drop test fixture weighing 357 pounds attached to the CCO end drop test article that was dropped in an inverted vertical orientation to axially impact directly onto the essentially unyielding drop pad surface. The test conservatively simulated the interaction between a CCO in a lower seven-pack array and a CCO in an upper seven-pack array inside a TRUPACT-II. The test article was oriented to maximize the loads on the closure interface. The test configuration neglected both the impact-attenuating characteristics of the packaging (e.g., honeycomb payload spacers) and the compliance of the other axially adjacent CCO in the stacked 14-pack arrangement to maximize the impact accelerations on the CCC and crush deformation of the dunnage assemblies.

Post-drop inspection of the CCO indicated measurable crushing of the 55-gallon drum and internal plywood dunnage assemblies that resulted in a minimum effective height of the CCO that measured between 31⅛ inches and 32 inches (pre-drop height of the 55-gallon drum was 35 inches). The upper and lower plywood dunnage assemblies experienced a corresponding axial crush deformation, but the assemblies attenuated the impact and prevented any direct interaction between the CCC and the test fixture/pad. The measured accelerations due to impact were recorded with filtering of the data utilizing a low-pass Butterworth 10-pole filter having a 250 Hz cut-off frequency. A minimum impact acceleration peak, from one reporting sensor, of approximately 411 g's was recorded.

Disassembly of the CCO and inspection of the CCC indicated no permanent plastic deformation of any of the confinement boundary components, essentially unaltered preload of the closure bolts (maximum bolt rotation to achieve installation torque values of 5°), and no loss of confinement as confirmed via ultraviolet light inspection of the assembly with no presence of the fluorescein indicator on the exterior surfaces.

Figure 12 shows the CCO end drop test article and test fixture assembly prior to the drop test. Figure 13 shows the assembly during and after the end impact event. Figure 14 shows the post-test measurement of the effective axial height of the CCO and associated axial crushing of the dunnage assemblies. Figure 15 shows the CCC after the post-drop test confinement evaluation and bolt residual torque confirmation process, indicating no degradation of the confinement vessel.

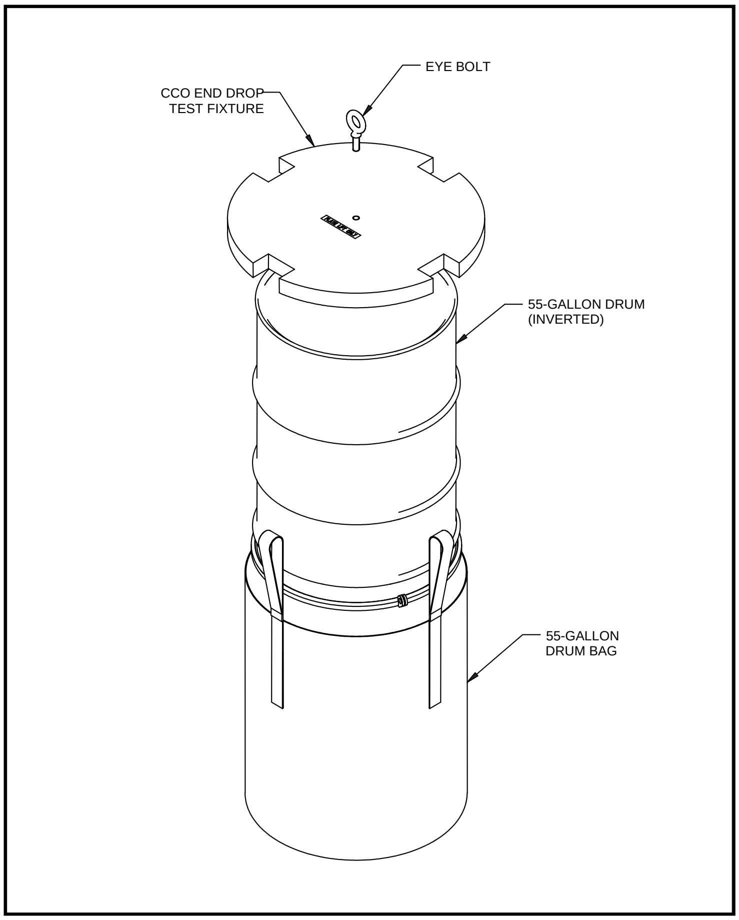

Figure 11. End Drop Fixture

Figure 12. Pre End Drop

Figure 13. During and Post End Drop

Figure 14. CCO End Drop Inspection

Figure 15. CCC End Drop Inspection

Summary of Testing

Key test observations included the following:

1. **1.** Post-test visual inspection of the exterior dimensions of the CCO indicated crushing of the upper and lower plywood dunnage assemblies such that the CCC experienced no direct impact with the external impacting surfaces of the test fixture and/or the test pad. The CCC experienced no measurable deformation.
2. **2.** The test conditions maximized the crushing of the upper and lower plywood dunnage assemblies by dropping at an elevated temperature using rigid test fixtures to simulate interaction with other CCOs in the payload assembly and by dropping directly onto an essentially unyielding surface rather than onto the impact-attenuating shells and polyurethane foam of the TRUPACT-II and/or HalfPACT ICV/OCA structures.
3. **3.** The CCC closure bolts retained essentially full residual torque, where the polar deviation to return the bolts to the initial installation torque was such that 99% of the gasket compression was retained after the drop event. In addition, the flour/fluorescein mixture placed within each CCC was 100% retained throughout the testing. Collectively, these observations readily confirmed confinement integrity of the CCO.

In summary, the results of the testing program for the CCO demonstrated that under HAC the CCO maintains confinement integrity, shielding integrity, and provides defined array spacing for criticality control purposes.

THERMAL EVALUATION

Thermal Evaluation for Normal Conditions of Transport

Thermal analysis models of the TRUPACT-II and HalfPACT packagings with a CCO payload were developed using the computer programs Thermal Desktop[2] and SINDA/FLUINT[3]. The thermal models are a three-dimensional half-symmetry (180º) finite element and finite difference solid element and surface/planar element and thermal entity representations of the packages. Identical modeling approaches were used for the thermal models for the TRUPACT-II and HalfPACT packages with appropriate modifications for the payload cavity height, number of installed payload containers, and decay heat limits and distribution. The heat transfer between the various components within the CCOs, between the CCOs and the ICV, and between the ICV/OCA is via radiation and conduction. Convection within the payload cavity was conservatively ignored. Heat transfer between the exterior of the package and the environment is via radiation and natural convection.

The analyses assumed that all packaging components were radially centered and all CCO components were radially and axially centered to maximize payload temperatures. All void spaces within the CCO and packaging cavity were assumed to be filled with air at atmospheric pressure. A paper-based waste stream with the effective conductivity of air was assumed for the payload with a maximum total decay heat loading of 40 watts for the TRUPACT-II package and 30 watts for the HalfPACT package. The distribution of decay heat was varied within the assembly of CCOs to establish the limiting case under the restriction that the maximum decay heat in any single CCO is limited to 20 watts. The decay heat within a CCO was assumed to be equally distributed within the waste volume on a volumetric basis. The package is mounted in an upright position on its transport trailer or railcar for NCT. This establishes the orientation of the exterior surfaces of the package for determining the free convection heat transfer coefficients and insolation loading. Insolation was applied in 12-hour “off/on” steps, i.e., a repeating 12-hour “off”, 12-hour “on” cycle for a sufficient period of time (1,200 hours) to allow the hottest location within the package to reach pseudo-steady-state equilibrium.

As summarized below, a set of four primary TRUPACT-II package and four primary HalfPACT package cases were evaluated, both without and with insolation.

For the TRUPACT-II package:

- Case 1: 40 watts decay heat evenly distributed in 14 CCOs (2.857 watts each); basic uniform decay heat load case for comparison with existing TRUPACT-II package and payload temperature results.
- Case 2: 40 watts decay heat evenly distributed in the 2 center CCOs (20 watts each); maximum heat load per CCO case with the highest thermal isolation (i.e., centered) that should produce the highest CCO contents temperature.
- Case 3: 40 watts decay heat evenly distributed in 2 axially aligned outer CCOs (20 watts each); highest ICV and OCV seal temperature case, along with Case 4.
- Case 4: 40 watts decay heat evenly distributed in 2 laterally aligned outer CCOs (20 watts each); highest ICV and OCV seal temperature case, along with Case 3.

For the HalfPACT package:

- Case 1: 30 watts decay heat evenly distributed in 7 CCOs (4.286 watts each); basic uniform decay heat load case for comparison with existing HalfPACT package and payload temperature results.
- Case 2: 20 watts decay heat in the center CCO and 10 watts decay heat in one outer CCO; maximum heat load per CCO case with the highest thermal isolation (i.e., centered) that should produce the highest CCO contents temperature, along with Case 3.
- Case 3: 20 watts decay heat in the center CCO and 10 watts decay heat evenly distributed in the 6 outer CCOs; maximum heat load per CCO case with the highest thermal isolation (i.e., centered) that should produce the highest CCO contents temperature, along with Case 2.
- Case 4: 30 watts decay heat evenly distributed in 2 laterally aligned outer CCOs (15 watts each); highest ICV and OCV seal temperature case.

Selected results of the NCT thermal analyses for HalfPACT and TRUPACT-II, Cases 2 and 3, are provided in Figure 16 and Figure 17, respectively. All maximum packaging temperatures and all maximum CCO temperatures are below the respective component maximum allowable temperatures.

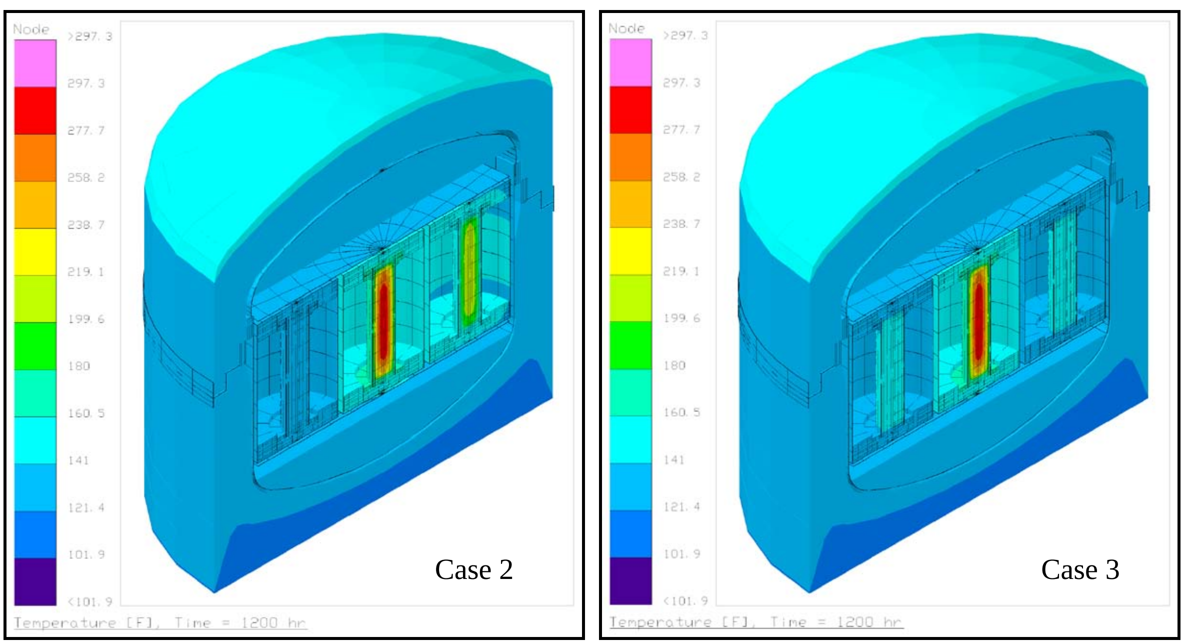

Figure 16. HalfPACT with CCO NCT Thermal Results with Insolation

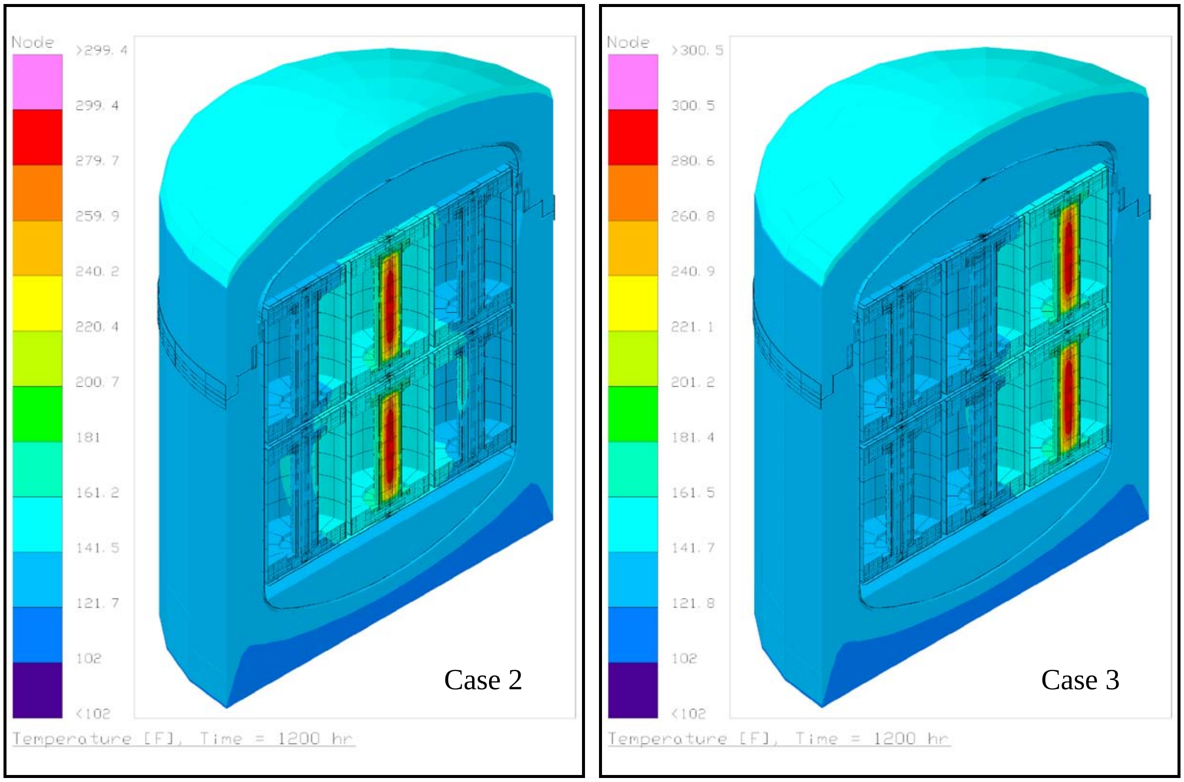

Figure 17. TRUPACT-II with CCO NCT Thermal Results with Insolation

Thermal Evaluation for Hypothetical Accident Conditions

The maximum temperatures for the CCO components within the TRUPACT-II and HalfPACT packagings from the HAC fire event were determined by conservatively combining the experimentally derived differential temperatures measured from the original HAC fire testing of each package containing a 55-gallon drum payload assembly with the worst-case initial pre-fire temperatures from the CCO NCT analyses. Further conservatism was attained by upwardly adjusting maximum temperatures to account for the difference in the tested payload mass versus the CCO payload mass.

The bounding estimate for the increase in TRUPACT-II and HalfPACT packaging component temperatures due to the lighter CCO payload is determined by taking the heat absorbed by the test payload (i.e., concrete-filled 55-gallon drums) and proportionally redistributing all of that thermal energy to packaging components interior to the OCA outer shell (which is already at the maximum fire temperature of 1,475 ºF and incapable of absorbing additional energy). The heat absorbed by the test payload was conservatively calculated by assuming a uniform temperature increase such that the payload bulk average temperature is assumed to be equal to the measured drum shell temperature. The adjusted absorbed heat values were subsequently used to calculate adjusted bulk average temperatures for the packaging components (i.e., OCA foam, OCV structure, ICV structure, honeycomb spacers, payload pallet, and, for the HalfPACT package only, the payload spacer) by using their respective component masses and specific heats. The adjusted packaging component bulk average temperatures were then used to calculate a bounding temperature change (percentage increase) due to a fire event for the package with "no payload" mass.

The "no payload" temperature change percentages were conservatively applied to the packaging components and CCO payload by assuming that the CCO 55-gallon drum adjusted maximum temperature is equal to the adjusted ICV bulk average temperature, with all other packaging component adjusted maximum temperatures equal to the maximum measured fire temperatures increased by the bulk average temperature change percentage for each component. It was conservative to assume that the CCO

55-gallon drum shell is at the bulk average temperature of the ICV structure because, at the point of maximum temperature, heat flow is primarily inward such that the magnitude of temperature increase due to the fire event is progressively less for each component as the heat moves from the OCV to the ICV and into the payload. Additionally, previous fire tests have demonstrated that the maximum surface temperature of the payload container(s) is less than the bulk average temperature of the ICV structure. To account for the pre-fire temperature gradients within the CCO that are due to the insulating effects of the radial gap between the CCC structure and the 55-gallon drum, the maximum temperature differential for each CCO component was assumed to be a function of the maximum temperature differential for the 55-gallon drum and proportional to the pre-fire temperature gradients within the CCO.

Table 1 and Table 2 for the TRUPACT-II and HalfPACT packages, respectively, summarize the predicted HAC temperatures for the major components in each package, none of which exceed defined temperature limits for the materials of construction.

Table 1. Predicted TRUPACT-II Package HAC Temperatures (ºF) with a CCO Payload

	TRUPACT-II SAR			CCO Analysis		
Component/Location	**Pre-Fire CTU**	**Adjusted Max Fire**	**Adjusted Max ΔT**	**Pre-Fire CCO**	**Post-Fire CCO**	**Limit**
Maximum CCC Structure	—	—	51.5	163.8	215.3	2,600
Maximum CCC Gasket	—	—	55.6	151.8	207.4	548
Maximum CCO Plywood Dunnage	—	—	57.9	145.7	203.6	482
Maximum CCO 55-Gallon Drum	127.0	190.4	63.4	133.1	196.5	2,750
Bulk Average ICV Cavity Air	127.0	182.4	55.4	123.4	178.8	N/A
Maximum ICV Structure	127.0	224.2	97.2	126.9	224.1	2,600
Maximum ICV O-ring Seal	127.0	203.8	76.8	123.2	200.0	360
Maximum OCV Structure	127.0	450.4	323.4	125.1	448.5	2,600
Maximum OCV O-ring Seal	127.0	259.6	132.6	118.4	251.0	360

Table 2. Predicted HalfPACT Package HAC Temperatures (ºF) with a CCO Payload

	HalfPACT SAR			CCO Analysis		
Component/Location	**Pre-Fire CTU**	**Adjusted Max Fire**	**Adjusted Max ΔT**	**Pre-Fire CCO**	**Post-Fire CCO**	**Limit**
Maximum CCC Structure	—	—	60.2	160.1	220.3	2,600
Maximum CCC Gasket	—	—	65.1	147.9	213.0	548
Maximum CCO Plywood Dunnage	—	—	68.2	141.2	209.4	482
Maximum CCO 55-Gallon Drum	43.0	118.2	75.2	128.1	203.3	2,750
Bulk Average ICV Cavity Air	43.0	121.6	78.6	121.5	200.1	N/A
Maximum ICV Structure	43.0	121.6	78.6	122.3	200.9	2,600
Maximum ICV O-ring Seal	43.0	121.6	78.6	119.1	197.7	360
Maximum OCV Structure	43.0	226.4	183.4	120.7	304.1	2,600
Maximum OCV O-ring Seal	43.0	226.4	183.4	115.6	299.0	360

CRITICALITY EVALUATION

CCOs are designed to transport transuranic (TRU) waste forms with high fissile material concentrations within the TRUPACT-II and HalfPACT packages. A criticality evaluation was performed for payload contents that are manually compacted (i.e., not machine compacted) and contain less than or equal to 1%

by weight quantities of special reflector materials. A maximum 380 fissile gram equivalent (FGE) of Pu-239 per CCO is justified for waste forms meeting these requirements.

For manually compacted waste with less than or equal to 1% by weight quantities of special reflectors, the moderator and surrounding reflector within each CCC was modeled as a composition of 25% polyethylene, 74% water, and 1% beryllium (by volume). As polyethylene is a superior moderator to water, this composition results in higher reactivities than would be achieved by water moderation alone. This volume fraction of polyethylene is conservatively higher than the maximum value achievable for manually compacted (i.e., not machine compacted) waste determined by experiment. Beryllium is a superior reflector to either water or polyethylene, and the inclusion of beryllium is conservative, although at such a small volume fraction, the beryllium has only a small effect on the system reactivity. The reactivity of CCOs in a HalfPACT package is bounded by the TRUPACT-II analysis. The HalfPACT and TRUPACT-II are essentially identical packages, although the HalfPACT payload region is approximately half the height of the TRUPACT-II. Thus, the single layer of seven CCOs in the HalfPACT package have a lower reactivity than the TRUPACT-II package, which has twice the fissile material. For this reason, calculations were performed only for the TRUPACT-II geometry.

Calculations for the TRUPACT-II package were performed using the three-dimensional Monte Carlo transport theory code, KENO-V.a v4.0, with the CSAS25 utility being used as a driver for the KENO-V.a code; both programs are part of the SCALE-PC v4.4[4] code system. In this role, CSAS25 determines nuclide number densities, performs resonance processing, and automatically prepares the necessary input for the KENO-V.a code based on a simplified input description. The 238 energy-group (238GROUPNDF5) cross-section library based on ENDF/B-V cross-section data is used as the nuclear data library for the KENO-V.a code. The upper subcritical limit (USL) for ensuring that the TRUPACT-II and HalfPACT is acceptably subcritical, as determined in benchmark evaluations, is: USL = 0.9377. Each package is considered to be acceptably subcritical if the computed k_{safe} (k_s), which is defined as $k_{effective}$ (k_{eff}) plus twice the statistical uncertainty (σ), is less than the USL, or: $k_s = k_{eff} + 2\sigma < USL$.

In both the NCT and HAC cases, the TRUPACT-II was modeled with reduced outer dimensions consistent with a damaged package. The torispherical heads were also modeled as flat, which brings fuel in stacked packages into close proximity. The steel 55-gallon drum of the CCO was ignored in all models, which is conservative because the steel would absorb neutrons and lower the reactivity. In the NCT models, the spacing provided by the drums is preserved. In the HAC models, reduced drum dimensions consistent with accident geometry were modeled, resulting in a highly compressed array within the package. Representative NCT and HAC SCALE models are shown in Figure 18. Fuel was modeled as pure Pu-239 homogeneously mixed with a moderator consisting of 74% water, 25% polyethylene, and 1% beryllium (by volume). This is a more reactive moderator than pure water and bounds the observed polyethylene volume fraction in the waste stream. Special reflectors (other than beryllium) that are in >1% by weight quantities are allowed if they are chemically or mechanically bound to the fissile material. The height of the fissile mixture was varied to optimize the moderation. Also, because the drums are stacked in two layers within the ICV, fuel was conservatively arranged so that the fuel is at the bottom of the top layer and at the top of the bottom layer. In all models, the fissile material within each CCC was assumed to form a single optimally moderated cylinder.

The most reactive case was for the HAC array. The HAC array was modeled with an infinite number of packages in the x and y directions, and two packages in the z direction. Because of the infinite number of packages and internal moderation within the CCCs, the HAC array is most reactive with no reflecting material inside the package. The most reactive case has $k_s = 0.9357$, which is below the USL of 0.9377. Addition of any reflecting or moderating material causes a decrease in reactivity. The NCT array shows the same behavior. For the single package cases, maximum reactivity was achieved with some internal reflector. For the NCT single package, the most reactive condition was with the 74/25/1 water/polyethylene/beryllium mixture inside the CCC and full-density water in all other package regions. The presence of plywood dunnage had little influence on the result. For the HAC single package, the most reactive condition was similar to the NCT single package, except with void between the CCC and drum. The system behavior for the HAC single package differed from the NCT single package as a result of the reduced drum diameter in the HAC models. However, the single package reactivity was significantly less than the array reactivity.

When maximally loaded with CCOs containing 380 FGE each, the TRUPACT-II and HalfPACT are limited to 5,320 FGE and 2,660 FGE, respectively. The criticality analysis results are summarized in Table 3.

Figure 18. CCO Criticality Models

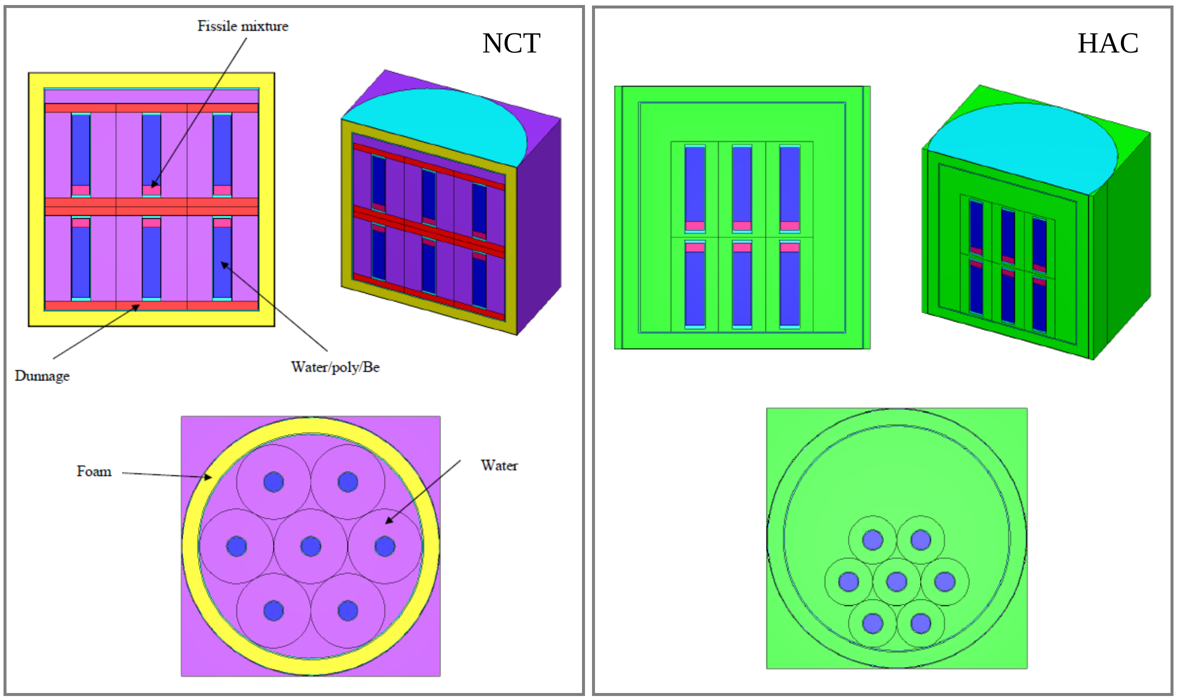

Table 3. Summary of Criticality Evaluation Results for 380 FGE per CCO

Normal Conditions of Transport (NCT)	
Case "I"	$\mathbf{k_s}$
Single Unit Maximum	0.8033
Infinite Array Maximum	0.9002
Hypothetical Accident Conditions (HAC)	
Case "I"	$\mathbf{k_s}$
Single Unit Maximum	0.8209
Infinite Array Maximum	0.9357
USL = 0.9377	

REFERENCES

[1] Petersen Inc., *Criticality Control Overpack 30-Foot Free Drop Post-Test Summary Report*, Engineering Report 8448-R-001, Rev. 1, Ogden UT, March 2011.

[2] Thermal Desktop®, *A CAD Based System for Thermal Analysis and Design*, Version 5.4, Cullimore & Ring Technologies, Inc., Littleton, CO, 2011.

[3] SINDA/FLUINT, *General Purpose Thermal/Fluid Network Analyzer*, Version 5.4, Cullimore & Ring Technologies, Inc., Littleton, CO, 2011.

[4] *SCALE4.4: Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers*, RSICC code package C00545/MNYCP00, Oak Ridge National Laboratory, September 1998.